

Environmental changes in SE Estonia during the last 700 years

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Sediment sequences retrieved from three lakes in southeastern Estonia were analysed for lithology, pollen stratigraphy and high-resolution loss-on-ignition (LOI) to study the environmental changes during the last 700 years. Age control was provided by varve counts, AMS ^{14}C and ^{210}Pb dates complemented by ^{137}Cs and ^{241}Am measurements, which confirmed the annual character of the sediments. LOI results displayed several periods with reduced values of organic matter and increased mineral matter fluxes. Organic production in the lakes and on the catchment was sensitive to climate change and human impact, while mineral load was mostly determined by external factors, which promoted soil erosion and influx into the lake. During the last 700 years in the environmental history of SE Estonia the three main phases were distinguished: low land-use phase between AD 1300 and 1750, extensive arable farming phase at AD 1750 and 1940 and diminished arable farming phase since AD 1940. This study showed, that the formation and development of the landscape in SE Estonia during the last 700 years was characterized by rapid changes in vegetation and lake sediment composition determined mostly by human impact, certain historic processes and climate change.

Introduction

Sedimentary processes in the lakes of the temperate zone have a cyclic character and in certain conditions they are reflected as annual laminations. The well-developed seasonal contrasts, spring floods and water column stratification are the main causes of the formation of laminated sediments in the boreal environment (Ojala *et al.* 2000, Lotter and Birks 2003). Laminated sediments were described from small and large lake environments, especially during the last years (Pettersen 1999, Snowball *et al.* 2003, Zillén *et al.* 2003). In Estonia, the first attempt to study the

Holocene laminated sediments had been made at the end of the 1980s (Rõuk 1986, 1992) but these studies died down for almost 15 years. In recent years, SE Estonia has become the focus of intensive palaeoecological studies and now ten pollen diagrams are available from this region (Mäemets 1983, Ilves and Mäemets 1987, Punning *et al.* 1995, Saarse and Rajamäe 1997, Laul and Kihno 1999). The investigations intensified at the end of the 1990s when the annually laminated lake sediments were found in deep lakes of the southeastern Estonia (Veski *et al.* 2004, 2005, Niinemets and Saarse 2006). For the present study three lakes (Kasaritsa Verijärv, Lasva and Rõuge



Fig. 1. Location of the study area and position of the examined lakes.

Tõugjärv) were selected because of the best preserved lamination and rapid sedimentation rate to provide high-resolution sediment records.

The main aims of the study were: (1) to reconstruct changes in vegetation and sediment composition during the last 700 years and to assess which factors triggered these changes; (2) to compare LOI results with reconstructed winter and summer temperatures to find out if temperature has affected the sediment composition; (3) to detect major phases of environmental development and answer the question how the land-use has changed in mosaic landscape. To achieve these aims pollen and loss-on-ignition proxies were used. Pollen record is most widely used tool to detect changes in vegetation and human impact (Behre 1981) and loss on ignition provides estimates of organic matter, carbonates and mineral compounds (Finsinger *et al.* 2006). Varve counts and AMS ^{14}C , ^{210}Pb , ^{137}Cs and ^{241}Am dating were applied to provide a reliable chronology.

Environmental conditions of the selected sites

Lakes Kasaritsa Verijärv, Lasva and Rõuge Tõugjärv (thereafter Verijärv, Lasva and Tõugjärv) in SE Estonia (Fig. 1) are located in the ancient valleys of a hilly terrain of the last glaciation on the Haanja Heights and near it. The

relief is built up of Quaternary sediments dominated by hills, valleys and kettle-hollows with numerous lakes. The studied lakes are thermally stratified and their bottom water is depleted in oxygen (Mäemets 1977).

The lakes are situated in the southeastern corner of Estonia characterized by the continentality of climate (Jaagus 2002), large temperature range, long lasting and thick snow cover, high amount of precipitation (up to 700–750 mm yr⁻¹), diversity of soils and microclimate conditions. Still, the annual average temperature (6–6.6 °C) is higher than in more eastern areas lying on the same latitude. The moraine hills are wooded by Scots pine, which is the most widespread species here, followed by Norway spruce and birch forests with scattered alder, aspen and other hardwood species.

Eutrophic Verijärv (57°48'30"N, 27°03'30"E) with an area of 20 ha and maximum water depth 19.4 m lies at an altitude of 88.4 m a.s.l. in the crossing of two deep ancient valleys on the northern slope of the Haanja Heights and has a bow-shaped configuration sheltered from wind by 30-m high hill-slopes from all sides. The present-day hard-water drainage lake has one outlet and receives water through two inlet streams and several bottom springs.

Lasva (57°51'30"N, 27°10'30"E; altitude 71.1 m a.s.l., size 10.9 ha, maximum water depth 19.2 m) is located about 9 km northeast of Verijärv, in the Võru-Hargla valley, which separates the Haanja and Otepää Heights. Hard-water eutrophic Lasva has an inflow stream from the south and a weak outflow to the north.

Tõugjärv (57°44'30"N, 26°54'15"E) on the western part of the Haanja Heights is located 10 km southwest of Verijärv. Tõugjärv is a hard-water kettle-hole lake in a deep Rõuge ancient valley, within a chain of seven lakes surrounded by steep slopes. Tõugjärv is mesotrophic, fed by stream water from an upper lake. It is smallest (area only 4.2 ha) but highest (elevation 107 m a.s.l.) among the studied lakes with maximum water depth 17 m.

Material and methods

In the early spring of 2001 and 2002 four parallel

sediment slabs were extracted from the central deepest part of the ice covered lakes. Extraction was done with a crust-freeze corer from the uppermost water-saturated sediment, and two overlapping sediment cores from the rest of the sequences with a Belarus (Russian) peat sampler. The cores were described visually in the field, photographed, wrapped into plastic and transported to the laboratory. Detailed digital images of cleaned cores were processed using imaging software. The varves were counted independently by different analysts directly from the sediment surface and from the digital images.

In order to control the age scale of annual lamination, ^{210}Pb dating and accelerator mass spectrometry (AMS) ^{14}C were carried out. The AMS ^{14}C dating of the terrestrial macrofossils and bulk organic rich sediment slices were performed in the Ångström Laboratory of Uppsala University and in the Poznan radiocarbon laboratory, ^{210}Pb chronology was determined in the Laboratory of the Center for Environmental Monitoring and Technology in Kiev, Ukraine. The selection and pre-treatment of macrofossils for AMS dating followed Wohlfarth *et al.* (1998). The radiocarbon ages were corrected for $\delta^{13}\text{C}$ and calibration of the dates was carried out to a confidence level of 1σ , using the Intcal98 program by Stuiver *et al.* (1998).

^{210}Pb , ^{137}Cs and ^{241}Am analyses were applied to the topmost sediments of Tõugjärv and Verijärv. ^{210}Pb activity was measured by direct gamma assay, CRS (constant rate of supply) Pb dating model was accepted to determine dates.

Continuous 1-cm-thick samples were used for loss-on-ignition (LOI) analyses to estimate the content of organic and mineral matter and carbonate compounds in all three sequences (Bengtsson and Enell 1986, Heiri *et al.* 2001). The organic matter (OM) content was measured by LOI at 550°C and expressed in percentages of dry matter. The percentage of carbonate content (CaCO_3) was calculated after burning of LOI residue for two hours at 900°C . The amount of residue, containing clastic material was described as a mineral matter. LOI analysis is a rapid method, inexpensive and easy to perform, which gives information on sediment stratigraphy and helps correlation between cores.

Pollen of all three sequences were analyzed

(Veski *et al.* 2005, Niinemets and Saarse 2006, Niinemets and Saarse, unpubl.). Pollen preparation followed the standard approach (Fægri and Iversen 1989) and ca. 1000 terrestrial pollen grains were counted in nearly all samples. Two *Lycopodium* tablets were added before preparation to calculate pollen influx (Stockmarr 1971). The pollen diagram and LOI results were plotted with TILIA and TILIA-GRAPH programs (Grimm 1991). To describe the land-use changes in the mosaic landscape Verijärv diagram was selected because of rapid sedimentation rate, presence of annually laminated sediments and existence of detailed historical maps and documents. The percentage pollen diagram with selected taxa of Verijärv displayed tree taxa, as well as herbs associated with human activities. The zonation of pollen and LOI diagrams was done separately for every investigated site using optimal splitting by sum-of-squares in psimpoll (Bennett 1994).

Historical maps, quantitative data on population, farmland and domestic stock on manors Vastse- and Vana-Kasaritsa were derived from Estonian State Archive by K. Koppel (2005). These manors are located on the catchment of Verijärv: Vastse-Kasaritsa directly on the lake NE shore, and Vana-Kasaritsa 4 km to south.

Results

Chronology

As an average, 661 varves were counted from the topmost frozen slabs of Tõugjärv sequence, 230 from Lasva and 210 from Verijärv that gives a timeline of 661, 230 and 210 years as maximum. ^{210}Pb dates from Tõugjärv and Verijärv acknowledged that the counted couplets were annual, which encouraged us to use counts in the reconstruction of the age–depth curves taking into consideration also AMS ^{14}C results (Table 1 and Fig. 2). Unfortunately not all the AMS ^{14}C dates fit the age–depth model. Especially the date Ua-19533 from the Verijärv sequence was clearly too old, apparently due to the hard-water effect. Gamma counting of ^{137}Cs and ^{241}Am identified a peak at a depth of 31 cm in Verijärv sequence that was interpreted as resulting from

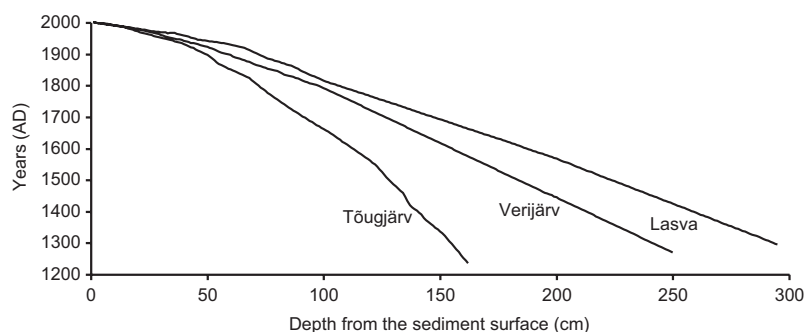


Fig. 2. Age/depth graphs of the studied sequences. The time scale was constructed on the base of varve counts, AMS and ^{210}Pb dates.

nuclear weapons testing in 1963 (Fig. 3a and c). This peak correlated rather well with the varve counts, which was dated to 1960 ± 3 . A sample at the depth of 15 cm showed a distinct peak from the Chernobyl event and correlated well with the varve of 1986. Similar picture was obtained for the Tõugjärv sequence (Veski *et al.* 2005). ^{210}Pb measurement displayed a sharp drop of unsupported ^{210}Pb between 40–55 cm (Fig. 3b) that could be caused by dilution of excess ^{210}Pb by accumulation of increased organic matter (Brenner *et al.* 2004). All ages given in text are years Anno Domini (AD).

Sediment lithostratigraphy and loss-on-ignition

All studied sequences were laminated, but lamination in intervals with organic matter higher than 30%–40% was poorly visible. The basic structure of a single varve was similar to the clastic-biogenic type described in Finnish lakes (Tiljander *et al.* 2003). The thickness of the varves differed considerably, and was greater

(commonly 5–10 mm) in the loose, uppermost sediment layer. Downward the thickness of the varves diminished. All examined sediment sequences contained 1–5 cm thick clayey bands.

Optimal splitting by sum-of-squares in psimpoll (Bennett 1994) recognized in Verijärv, Lasva and Tõugjärv three units (Fig. 4). Verijärv sequence differed by the increased organic matter content in the bottom unit I (up to 44%), low carbonate frequency throughout the studied profile (less than 8%) and the highest share of mineral matter in the second and third units (up to 86% and 79% respectively; Fig. 4a). The 11-year moving average graph displayed a slight reduction in the OM content around AD 1300 in Verijärv (Fig. 5a). Afterwards, the OM content increased and then stabilized for 250 years around 38%–40%. At about AD 1700 OM started to decrease and reached its minimum around AD 1800 (Fig. 5a). This was followed by a short-term increase up to 1870, stabilization at around 20% and since 1920 it has been rising again (Figs. 4a and 5a).

The LOI results of Lasva (Fig. 4b) sequence resembled those of Verijärv (Fig. 4a), however,

Table 1. AMS ^{14}C measurements from lakes Tõugjärv, Verijärv and Lasva. Calibrated ages are given with 1σ certainty.

Lake	Lab. no.	Depth (cm)	^{14}C age BP	δ^{13} (‰ PDP)	Dated material	Calibrated age (BC/AD)
Tõugjärv	Ua-19780	1786–1789	1400 ± 50	–30.8	bulk gyttja	605–665 AD
Tõugjärv	Ua-19532	1989–1991	3230 ± 60	–30.4	wood	1420–1600 BC
Verijärv	Ua-19533	1995	1590 ± 60	–41	aquatic moss	410–540 AD
Verijärv	Ua-19791	2047–2050	990 ± 50	–31.4	bulk gyttja	980–1120 AD
Verijärv	Ua-19534	2125	1365 ± 60	–42	wood	610–770 AD
Lasva	Ua-19792	2149	380 ± 50	–27.2	wood	1440–1630 AD
Lasva	Poz-13746	2330	1145 ± 30		macroremains	835–970 AD

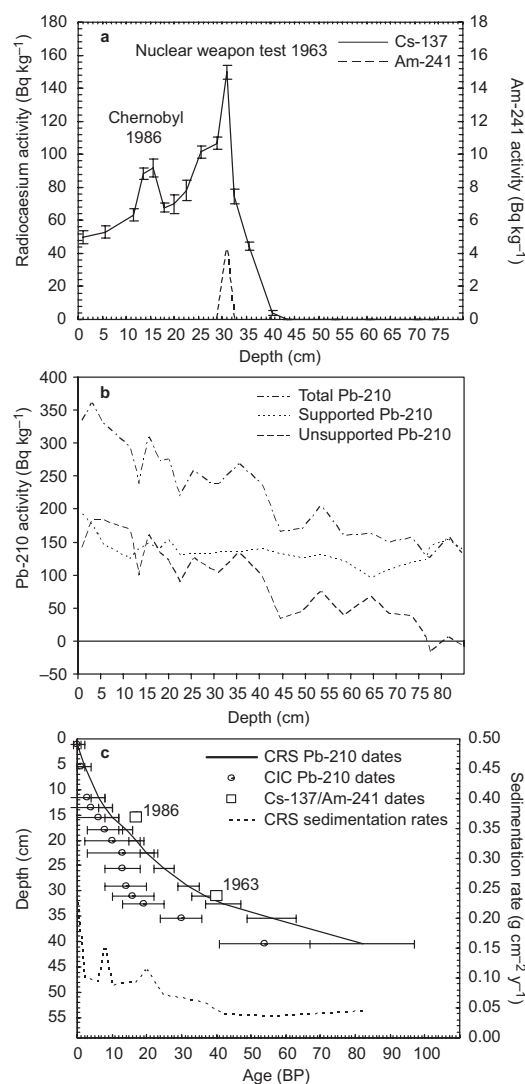


Fig. 3. Radioisotope activities in Verijärv sediment sequence. (a) ^{137}Cs and ^{241}Am activity versus depth, (b) results of total, supported and unsupported ^{210}Pb , (c) calculated ^{210}Pb dates using the CRS and CIC models. Analysis by G. Laptev.

mineral matter started to increase ca. 100 years earlier. 11-year moving average of OM displayed small fluctuations between AD 1300–1600, a decrease limited between AD 1600–1700, fluctuations around 20% between AD 1800–1950 and a pronounced increase afterwards (Figs. 4b and 5b).

Tõugjärv sequence is characterized by a relatively low proportion of OM (Fig. 4c), especially in the unit II (up to 19%) and increased carbonate

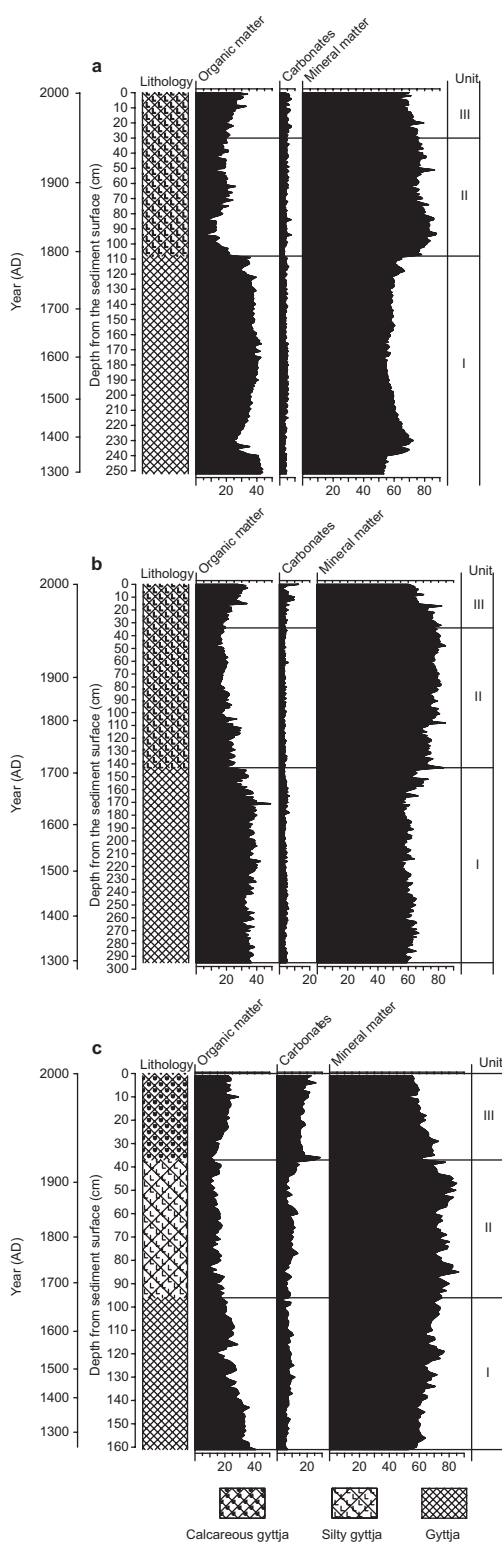


Fig. 4. Lithostratigraphy and loss-on-ignition (LOI) results. (a) Verijärv, (b) Lasva, (c) Tõugjärv.

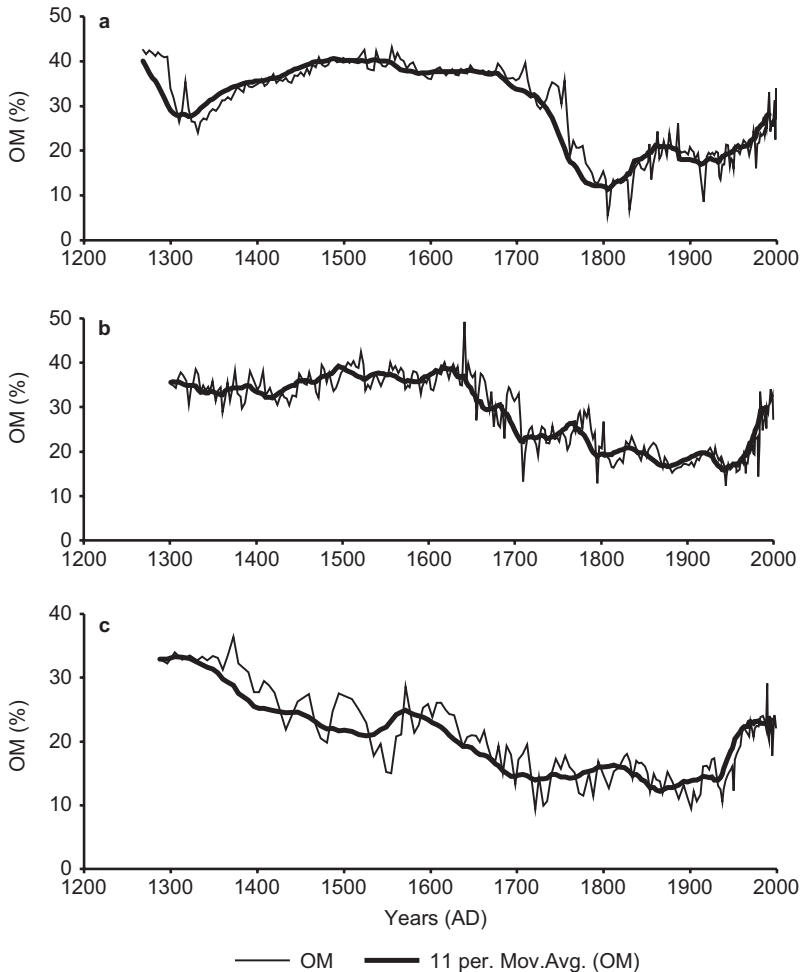


Fig. 5. Comparison of organic matter changes in different lakes as indicating 11-year moving averages. (a) Verijärv, (b) Lasva, (c) Tõugjärv.

content in the topmost unit (up to 29%; Fig. 4c). 11-year moving average curve of OM showed falling between AD 1300–1500 and 1600–1700, rise around 1550, 1820, and since 1930 onwards (Fig. 5c).

Pollen stratigraphy

In the pollen stratigraphy of the Verijärv sequence four local pollen assemblage zones (LPAZ) were distinguished (Fig. 6). LPAZ VJ4 comprised the time span up to AD 1350 and was characterized by the dominance of *Pinus* and *Betula* pollen, followed by *Picea* and *Alnus*. QM pollen frequency was negligible, represented mostly by *Quercus* and *Ulmus*. The continuous curve of *Secale* started accompanied with sporadic *Hordeum* and

Plantago lanceolata. At the end of VJ4 an abrupt rise of herb pollen occurred, among which pollen of ruderals and cereals prevailed (Fig. 6).

LPAZ VJ3 (AD 1350–1750) differed from the previous zone by a sharp reduction of tree pollen and rise in herbs. Cultivated plants were represented by *Secale cereale*, *Triticum* and sporadic *Hordeum*. *Fagopyrum esculentum* identified in sediments dated to AD 1470 (Fig. 6). Both palynological richness and charcoal percentages increased.

LPAZ VJ2 (AD 1750–1940) was represented by a maximum occurrence of herbs, particularly general apophytes, wet meadow taxa, ruderals and cereals. All the above-mentioned anthropogenic indicators reached their maximum. Tree pollen influx had remarkably decreased (Fig. 6).

LPAZ VJ1 (AD 1940–2000) covered the last

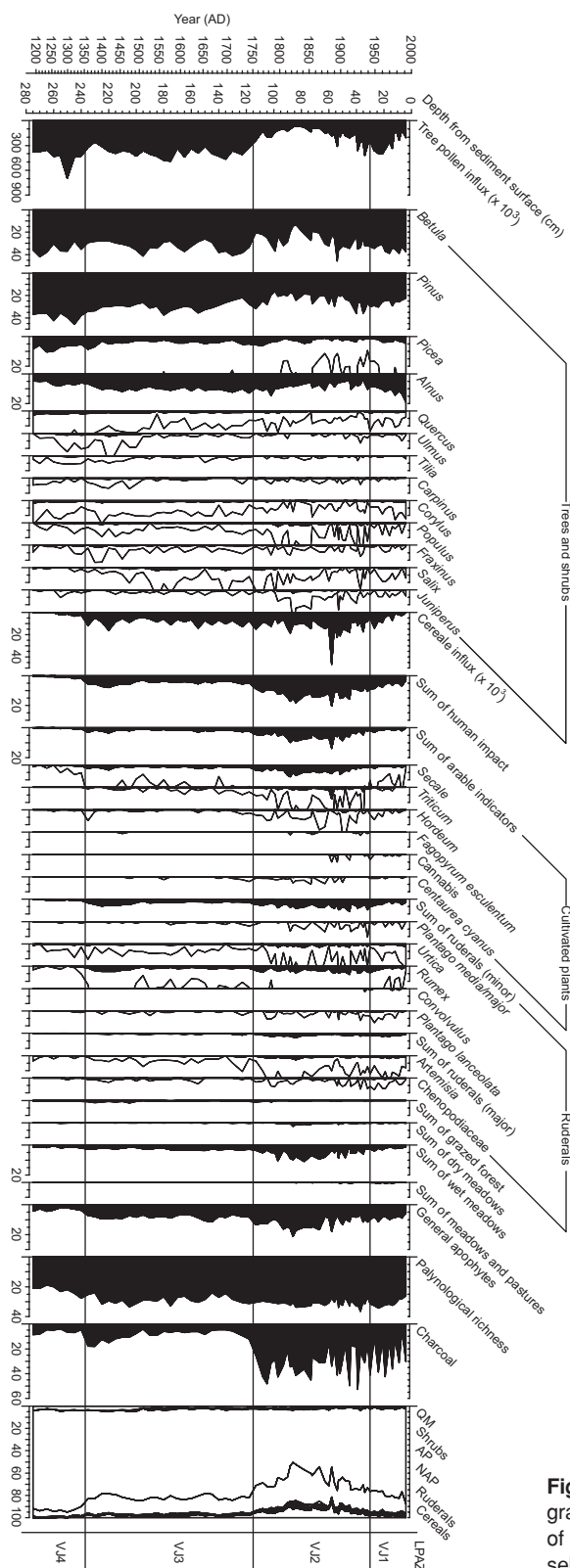


Fig. 6. Percentage pollen diagram from the uppermost part of the Verijärv core showing selected taxa.

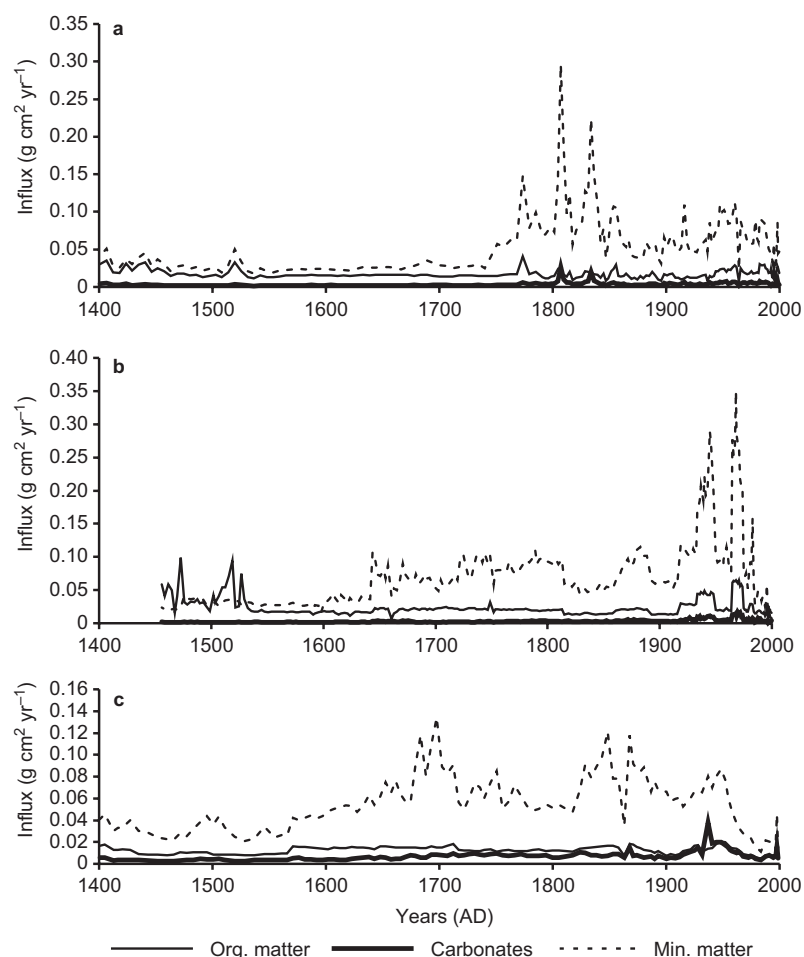


Fig. 7. Influx of organic, carbonate and mineral matter. (a) Verijärv, (b) Lasva, (c) Tõugjärv.

60 years during which almost all anthropogenic indicators, especially cultivated plants, diminished and the tree pollen frequency increased (Fig. 6).

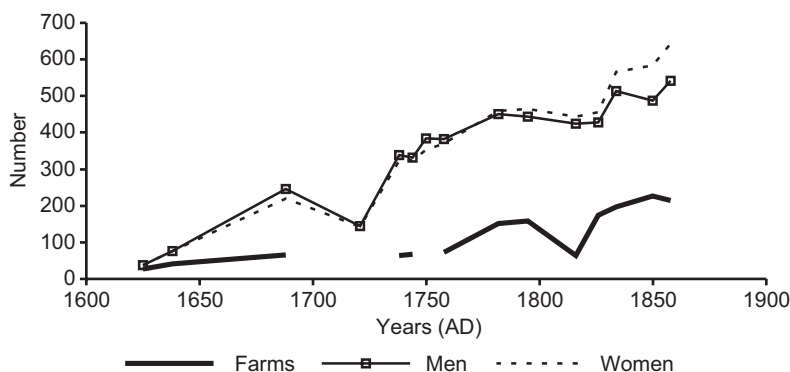
Discussion

Based on the pollen records and LOI results, three major periods in vegetation and land-use history were distinguished in the last 700 years in the studied area. The first period AD 1300–1750 is characterized as low land-use phase. It included lithological unit I (Fig. 4) and local pollen assemblages VJ3 and VJ4 (Fig. 6). Sediments deposited in this period were rich in organic matter, which shadowed the lamination and complicated varve counting except for

Tõugjärv sequence where the organic matter content was smaller. In the sediment composition mineral matter prevailed. Its influx depends mainly on external factors, such as the lake level fluctuation, soil erosion and agrarian activities in the catchment. At around AD 1600 mineral matter influx doubled in Lasva and Tõugjärv sequences (Fig. 7b and c), caused most likely by increased land-use. In Verijärv such increase has been observed since AD 1750 (Fig. 7a).

The pollen record from Verijärv provided evidence of gradual opening up of the landscape and a small-scale cereal cultivation before AD 1350 (Fig. 6). In VJ3 LPAZ (1350–1750) pollen percentages of tree taxa considerably diminished and herbs increased. The share of human impact indicators first increased, then remained almost unchanged throughout the entire phase. Cereals,

Fig. 8. Number of farms, men and women in Kasaritsa manors between AD 1625–1858. Compiled by K. Koppel on the base of different archive documents.



represented by *Secale* and *Triticum*, were constantly present, *Hordeum* occurred sporadically. The slash-and-burn agriculture was the main agricultural practice; evidence was derived from the doubling of charcoal (Fig. 6). The number of population and farms increased since AD 1625. During the Great Northern War (1700–1721) the population seriously suffered (Fig. 8); however, this event has not left remarkable traces into the land-use. Besides sparse population the primitive techniques used in farms and manors hindered large-scale crop farming. Lasva and Tõugjärvi pollen diagrams also displayed modest human impact, which changed to more intensive about AD 1650 (Veski *et al.* 2005, Niinemets and Saarse unpubl. data).

Climate reconstruction based on different local proxies from Estonia and reaching back to AD 1500 display low temperatures and severe winters between 1570–1650 (Tarand and Eensaar 1998, Tarand and Nordli 2001). According to Briffa *et al.* (1992) this cooler period lasted even longer, up to AD 1750 in Scandinavia. The mentioned cooler period was preceded between AD 1350–1550 by a warmer one, at least in Fennoscandia (Briffa *et al.* 1990, Cowling *et al.* 2001). These climate changes did not leave remarkable traces in sediment composition. Still, since AD 1600 OM content started to decrease in Lasva and Tõugjärvi sequences, but stayed on the previous level in Verijärvi (Fig. 5).

During the second, extensive arable farming period (AD 1750–1940) laminated silty gyttja deposited in all studied sequences intercalated with thick clayey bands, which on the influx graphs are reflected as sharp peaks (Fig. 7). As the timing of clayey bands differed, they were

interpreted as erosional events related to the local human induced changes on the catchment: forest clearances, drainage of meadows and pastures and regulation of water level in lakes. The increased mineral matter load into the lakes (Fig. 4, unit II) is in good accordance with the pollen record, which suggests higher cereal pollen percentages, sharp increase in charcoal particles and, thus, enlarged crop cultivation promoting soil erosion (Fig. 6, VJ2). The vegetation development was greatly affected by human activities. Tree pollen reached its minimum, herbs, cereals, ruderals and general apophytes met their maximum, which points to developed farming and grazing. Slash-and-burn agriculture was one of the main agricultural practices concluded from the rise of charcoal particles from 5% to 40% (Fig. 6). Large-scale forest clearances and establishment of fields near the lakes could be expected as herbs formed nearly 40% of total pollen in Tõugjärvi (Veski *et al.* 2005) and 20%–30% in Verijärvi pollen records (Fig. 6). This is in good accord with the demographic data and usage of draught animals, which showed that after the Great Northern War the number of farms quickly doubled and population increased about three times (Fig. 8; Koppel 2005).

According to different proxy data Estonia experienced severe winters and large temperature variations between AD 1780–1830 (at the end of the Little Ice Age) with anomalously cold winters in 1780, 1800, 1803, 1809, 1820 and 1829 (Tarand and Eensaar 1998). This also includes the historically documented strong El Niño year in 1791, which according to reconstruction has a global pattern (Mann *et al.* 1998). A sharp decrease of OM between AD 1780–

1820 in Verijärv sequence (Figs. 4a and 5a) and the low content of OM in the other studied sequences (Figs. 4b and c, 5b and c) apparently reflected this climate deterioration and possibly confirm that organic production is sensitive to the climate change. However, it cannot be ruled out that the coincidence of the organic matter decline and reconstructed colder climate could be occasional. Besides climate, there are several other local factors, first of all human activities, which, beyond doubt, influenced the bioproduction, minerogenic inflow and hydrology of the lakes. Since AD 1830 temperature started to increase and according linear trend amounts to +1.6 °C during the last 150 years (Tarand and Nordli 2001). Parallel moderate rise in OM content was observed only in Verijärv sequence (Fig. 5a). Other sequences displayed low organic matter content (Fig. 5b and c).

During the third period (AD 1940–2000) arable farming diminished. Laminated gyttja and calcareous gyttja deposited in the studied lakes, characterized by thick loose annual lamina and higher organic matter content, accompanied by the rise of carbonates in Tõugjärv sequence (Fig. 4). Increase in OM in sediment sequences could be result of reduced arable farming as well as increased microbial activities just beneath the surface of sediment. According to Wetzel (2001: p. 806) “both production and utilization of the organic matter are controlled to a great extent by regulating factors of inorganic and organic biochemical cycling”. Still, problems associated with diagenetic changes in organic compounds after deposition is little known (Wetzel 2001: p. 791). The mineral matter content diminishing to 60% caused mainly by declining arable farming and closing up the landscape, concluded from increased arboreal pollen, decreased cultivated plant pollen percentages and unstable charcoal frequencies (Fig. 6). Such decline in land-use was a result of abandonment of manors and deportation of farmers. Later, the collective farms preferred larger fields on more gentle topography, where modern technique was easier to manage and land more effectively used. Hills, once tilled by local farmers, were left to overgrow with shrubs and trees. Elevated nutrient load into lakes due to intensive fertilizing of fields brought about eutrophication (Ott and Kõiv 1999) and

accelerated accumulation of organic substances promoted by climate warming (Tarand and Een-saar 1998). So, higher content of organic matter could be interpreted as increased lake productivity and hence increased summer temperature, which coincide well with the instrumentally measured climatic parameters.

In conclusion, three main phases in the environmental history of SE Estonia were clearly reflected in the sediment sequences: (1) low land-use phase during AD 1300–1750, caused by sparse population and the primitive techniques; (2) extensive arable farming phase at AD 1750–1940 favored by dense population, wide use of draught animals on the hilly landscape and since 1870 of ameliorating climate; (3) diminished arable farming phase at AD 1940–2000 caused mostly by political reasons.

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